Paper presented at the *SEFI 36th Annual Conference*, 2-5 July 2008, Aalborg.

Conceptual labs as an arena for learning: Experiences from a decennium of design and implementation

Jonte Bernhard

Engineering Education Research Group, ITN, Campus Norrköping, Linköping University, SE-60174 Norrköping, Sweden (jonbe@itn.liu.se)

Abstract

A series of projects focusing on the design and implementation of "conceptual labs", aimed at developing insightful learning, are described. The work commenced in 1994/95 and has been followed by a series of projects. The main focus has been on courses in mechanics and electric circuit theory.

The approach taken in designing these innovative curricula coincides very well with the emergent paradigm described as "design-based research". In line with this emergent tradition, I describe how our designs have functioned in authentic settings and focus on interactions that have refined our understanding of the learning issues involved. A common feature in these learning environments is the use of technology as a tool for students' inquiry. Systematic variation, based on the theory of variation, has been introduced into task design.

According to results using conceptual inventories, the conceptual labs have been very successful. However, it has also been shown that learning is not determined by the technology but by the design of the tasks. In the later projects we studied students' courses of action in labs using video recordings. I describe how these studies have provided insights into critical conditions for learning and have helped us to improve learning environments further.

Keywords: Engineering education research, design-based research, lab-work, learning environment

1 INTRODUCTION

One important aim in engineering education is that students should *learn* to understand theories and models and their *relation* to objects and events in the 'real' world; they should also *learn* to *apply* these models and theories. During lab-work, in particular, students are expected to link observed data to theoretical models and to the objects and events they are exploring [1, 2].

In this paper I describe a series of projects focusing on the design and implementation of 'conceptual labs' aimed to develop insightful learning. The work started in 1994/95 and, subsequently, there has been a series of projects. The main focus has been on courses in mechanics and electric circuit theory and has involved courses for university students studying to become engineers as well as students studying to become teachers.

A necessary condition for learning, as noted by Ference Marton and his co-workers [3, 4] , is that students must be able to focus on the 'object of learning' and discern its critical features. The 'object of learning' is not a 'thing', but is a set of relations, concepts, theories, capabilities etc., that the students are supposed to learn (the intended object of learning). The critical aspects of the object of learning must enter the focal awareness of students. In their work they also pointed out that

> "people act … in relation to situations as they perceive, experience, and understand them. … If we want learners to develop certain capabilities, we must make it possible for them to develop a certain way of seeing or experiencing. Consequently, arranging for learning implies arranging for developing learners' ways of seeing or experiencing, i.e., developing the eyes through which the world is perceived" [5].

In a similar vein, I have previously [6] described a conceptual lab as one that help students to develop fruitful ways of linking concepts, models, objects and events. A conceptual lab or lecture demonstration is a *place of inquiry*, where students "ways of seeing or experiencing … the world [are developed]", i.e. the lab is an arena for further learning and not for confirmation of theories and formulas already taught in lectures. Similarly, knowledge, according to Rorty [7], is not "a matter of getting reality right, but a matter of acquiring habits of action for coping with reality". Knowledge is a "capability of handling novel situations in powerful ways" [5] and, following Dewey [8, 9], concepts are regarded as tools (see also Wells [10]).

2 THEORETICAL BACKGROUND AND FRAMEWORK

2.1 Design-Based Educational Research

In the last ten years, several non-conventional approaches to designing innovative curricula have emerged. These approaches have been described, as noted above, as "design experiments" [11] or "design-based research" [12-14]. Lo et al. [15] have described one of the main features of this approach as follows:

> "The benefits of design experiments are that we will be able to contribute to theory development, and improve practice at the same time."

According to The Design-Based Research Collective [14] design-based research "must account for how designs function in *authentic settings*. It must not only document success or failure but also *focus on interactions* that refine our understanding of the learning issues involved." Cobb et al. [11] described this shift thus:

> "Prototypically, design experiments entail both 'engineering' particular forms of learning and systematically studying those forms of learning within the context defined by the means of supporting them. This designed context is subject to test and revision, and the successive iterations that result play a role similar to that of systematic variation in experiments".

Our study has several features similar to those described above, including a focus on interactions in an authentic setting. Below, I describe ways in which we have implemented variation theory [4] in our design, and linked it to observed outcomes associated with students' performance.

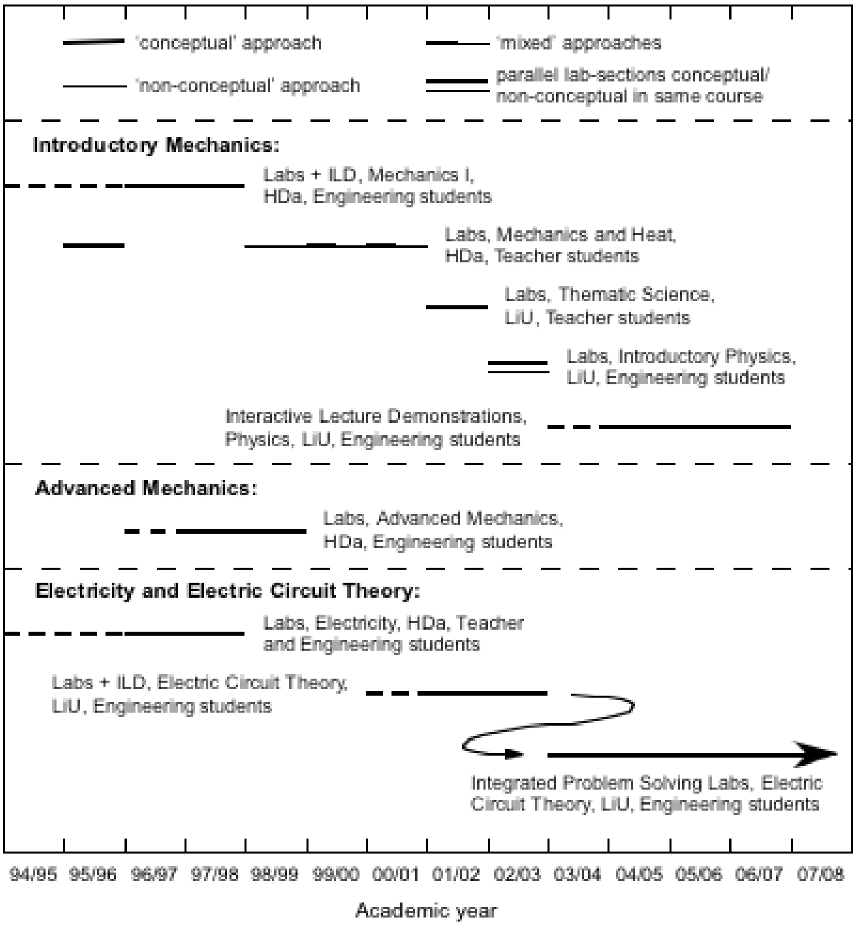

FIGURE 1. An overview of the learning environments developed and/or studied in connection with the larger 'project' of designing 'conceptual' labs and lecture demonstrations. The figure shows the type of course, its main student body and the academic year in which the course was run. The abbreviations used are: HDa – Högskolan Dalarna (Dalarna University), LiU – Linköping University and ILD – Interactive Lecture Demonstrations. Dashed lines denote trials or reduced early versions of curricula.

2.2 Mediating tools

An important theoretical background is the concept of tools in the socio-cultural theory of learning [16-18]. Much human interaction with the material and social world is not direct but mediated through the use of tools [19-21]; this can be expressed as:

> Human ⇔ Tools ⇔ World.

Such tools can be of different types, such as "psychological tools" or physical artifacts, and they facilitate more powerful and functional ways of acting. That we "think through technology" is also discussed by Mitcham [22] in a book of the same title, and in some schools of the philosophy of technology, thus extending the works of Dewey (see for example Hickman, [23]). Verbeek [24] further developed this concept and, according to him:

> "The concept of mediation helps to show that technologies actively shape the character of human–world relations. Human contact with reality is always mediated, and technologies offer one possible form of mediation. On the other hand, it means that any particular mediation can only arise within specific contexts of use and interpretation".

The use of tools is a dual process: humans both shape the world (including human culture) and are shaped by the use of tools. This means that humans are part of their world (and cannot remove themselves and view the world from the 'outside'). Wartofsky [25] expressed this as follows (p. 204):

> "I take the artifacts (tools and languages) to be objectifications of human needs and intentions … *already* invested with cognitive and affective content."

The philosopher of technology Don Ihde synthesised non-foundational phenomenology and pragmatism in an approach known as postphenomenology [26]. According to him, perception is co-determined by technology. In science, instruments do not merely "mirror reality," but mutually constitute the reality investigated. The technology used places some aspects of reality in the foreground, others in the background, and makes certain aspects visible that would otherwise be invisible [19, 27]. Neglecting the role of technology in science leads to naïve realism or to naïve idealism [27, 28]. Heidegger [29, p. 29] noted that technology both reveals aspects of the world – allowing us to see things that we previously could not perceive or were difficult to perceive – *and* frames our experience, i.e. shapes figure–background relationships.

2.3 Variation theory

Variation theory, developed by Marton and co-workers [3, 4, 30], provides an explanatory framework describing the conditions required for learning. Central to this theory is that we learn through the experience of difference, rather than the recognition of similarity. Being open to learning should be understood in terms of *discernment*, *simultaneity* and *variation*. Learning is seen as developing certain capabilities and values that enable the learner to handle novel situations in powerful ways.

Powerful ways of acting emerge from powerful ways of seeing, and our previous experiences affect the way in which we experience a new situation. Our perception also affects the experiences we consider to be relevant, and the power of actions in a given situation is relative to one's aims. Seeing something in a particular way is defined by the aspects that can be discerned by the observer at a certain point in time. The difference between 'discerning' and 'being told' should be noted. People discern certain aspects of their environment by experiencing variation. When one aspect of a phenomenon or an event varies, while one or more aspects remain the same, the one that changes will be discerned. One of the main themes of variation theory is that the pattern of variation inherent in the learning situation is fundamental to the development of certain capabilities. In the words of Marton, Runesson and Tsui [5]:

> "What we believe is that variation enables learners to experience the features that are critical for a particular learning as well as for the development of certain capabilities. In other words, these features must be experienced as dimensions of variation."

Experiencing variation amounts to experiencing different instances simultaneously. This simultaneity can be either *diachronic* (experiencing, *at the same time*, instances that we have encountered at different points in time) or *synchronic* (experiencing different co-existing aspects of the same thing at the same time). Marton, Runesson and Tsui [5] also introduce the concept of a learning space:

> "The space of learning tells us what it is possible to learn in a certain situation [from the perspective of a particular object of learning]. … The space of learning … is … an experiential space. …"

Marton and co-workers [4, 5, 31] distinguish between the *intended object of learning*, the *enacted object of learning* and the *lived object of learning*. The intended object of learning is the subject matter and the skills that the teacher or curriculum planner is expecting the students to learn. The enacted object of learning is the learning space produced within a learning environment, i.e. what it is actually possible for the student to learn. The lived object of learning is the way students see, understand, and make sense of the object of learning and the relevant capabilities that the students develop.

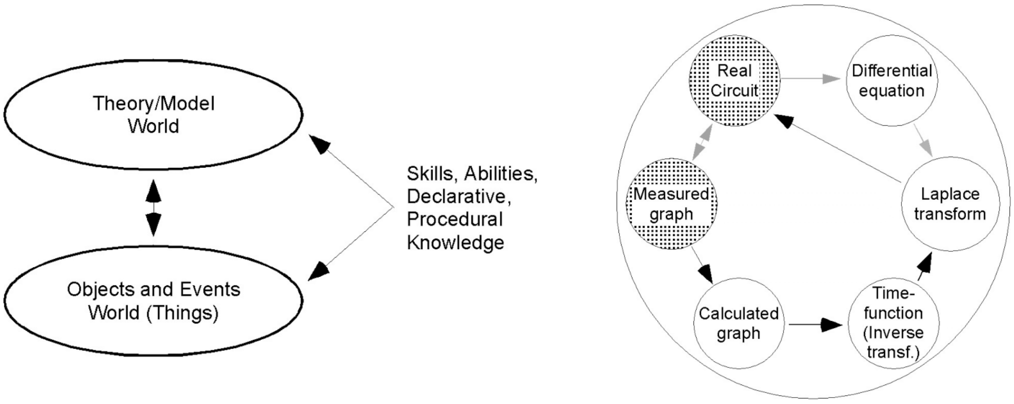

FIGURE 2. a) Categorisation of knowledge based on a modelling activity [32]. b) The categorisation in figure 2a has been developed further into the model of learning of a 'complex concept' [33-35]. In this case, translated and interpreted into the example of an electric circuit theory course lab about transient responses. The shaded circles represent knowledge located in the world of objects/events and the other circles knowledge in the world of theories/models.

2.4 Linking and modelling

During lab work, students are expected to link observed data to either theoretical models, or to the 'real world' that they are exploring. Tiberghien [36] proposed that the world of theories and models, and the world of objects and events can be seen as the main categories in the analysis of knowledge. It can be argued that this categorisation is very effective when analysing and developing learning environments, such as labs. According to recent research, students or novices have problems establishing relationships between the object/event world and the theory/model world. It is, therefore, important, when teaching, to make explicit the links between the theory/model world and the object/event world. For example, Vince and Tiberghien [32] state that "establishing relevant relations between the physics model and the observable objects and events is a very difficult task". Similarly Roth [37] found that students were "referentially stuck in the symbolic and associated conceptual representations, and experienced the phenomena as something unrelated" (see also work by Roth and Bowen [38]). At a physics education conference at Tufts University, the researchers present agreed on the following conclusion [39, 40]:

> "Connections among concepts, formal representations, and the real world are often lacking after traditional instruction. *Students need repeated practice in interpreting physics formalism and relating it to the real world*" (emphasis in the original).

At university level, the links students are supposed to make between the theory/model world and the object/event world are often links between mathematical models and measurement data, or graphs based on mathematical calculations and/or derived measurement data. This is often seen as the fundamental purpose of lab work [41]. Our research and studies by other authors have shown that these links do not occur spontaneously, even when the set task is to compare graphs derived from calculations with graphs based on measurements.

3 EVALUATION OF LEARNING RESULTS

In the mechanics part of this study we used the research-based conceptual test *Force and Motion Conceptual Evaluation* (*FMCE*) [42] to investigate the functional understanding of mechanics achieved by the students. The test uses multiple-choice questions to assess student conceptual understanding of mechanics. The distractors (wrong answers) are carefully chosen and correspond to common sense beliefs (misconceptions) as shown in the research literature on misconceptions. The multiple-choice format of FMCE makes it feasible to conduct controlled large-scale educational studies. The FMCE has been shown, by its developers, to provide reliable and valid measures of students' conceptual understanding of basic Newtonian mechanics [42]. Students' responses to the FMCE questions in an open ended format correlate very well to their answers in the multiple-choice format. The FMCE-test was given to the students during one of the first lectures as a pre-test (one lecture, 45 min, was set aside for this) and after the course was finished the test was administered as a post-test. In earlier work we have also made some use of the Force Concept Inventory-test (FCI) [43]. When evaluating the results from FCI-and FMCE-testing, we use a measure called normalised gain [44], defined as g = Gain/[Gain(max)]. Gain is the difference between pre- and post-test values.

Our early data from the FMCE-test show that if we create lab-instructions that apply teaching strategies in line with “variation theory” the students achieve better results than if the teacher adopts a “cookbook approach”. However, it is never possible to completely specify the enacted object of learning or the students’ courses of action in the labs [45]. This led to us examining the four interrelated questions below.

- In what different ways do the students approach the learning environment?
- How do the different approaches influence the students’ enacted object of learning?
- Which aspects of the learning environment direct the students towards the intended object of learning?
- How can we further develop these aspects?

Therefore, since 2001, we have recorded students’ courses of action using digital camcorders The data have been used to detect typical interactional patterns and find evidence of, or to reject hypotheses on, the generality of these patterns [46]. In the analysis, we have been inspired by an emerging research tradition that focuses on students’ interactions in science and mathematics education [47-50]. Furthermore, the analytical approach adopted is also influenced by ethnomethodology [51, 52], conversation analysis [53] and situative approaches to learning and cognition [47, 54, 55]. We have focused on central characteristics of learning environments and we have explored what the students do and which resources they use. Here, I present a fine-grained analysis, using probeware (also called MBL), giving some reasons for the success of certain curricula. Since it is important to show not only verbal contributions, but also what the students are doing, some data are presented in the form of drawings resembling comic strips (see figure 4) rather than traditional transcripts. Illustrating video data in this form is discussed in more detail in other publications within this wider project [56]. When analysing the labs in the electric circuit theory course, we applied the model of learning a complex concept described above. The different relational concepts are illustrated by “islands” (see figure 2b), and arrows show the links between the different concepts. This model can be used to analyse the intended links, or the links actually made by students, depending on whether “the intended object of learning” or “the lived object of learning” is being investigated.

4 CONCEPTUAL LABS

4.1 Lab-work

In recent decades there have been many attempts to create learning environments that are exploratory but also direct students’ attention towards relevant concepts and phenomena, so-called *guided discovery* [57, 58] or *interactive-engagement labs* [44, 59]. Thus, the labs are inquiry-driven, but the students are guided in their inquiry by carefully designed instructions, technology, and teacher support. Such attempts include curricular projects such as the Modelling Workshop Project [60] Socratic Dialogue Inducing Labs [61], RealTime Physics [62], and Tools for Scientific Thinking [63]. A common feature of the projects cited is that they make use of a technology called Microcomputer-Based Labs (MBLs) or computerised data logging. MBLs consist of a computer connected to a sensor or a probe; they are used in the collection, analysis, and display of experimental data by transforming the sensor’s signals into a graph on the computer screen.

The MBL is an example of the use of “interactive technology” in physics education [64]. MBLs were introduced into physics teaching almost three decades ago. In MBL activities, students perform experiments using different sensors (e.g., force, motion, temperature, light and sound sensors) connected to a computer via an interface. The arrangement creates a powerful system for the *simultaneous* collection, analysis and display of experimental data; this is sometimes referred to as *real-time* graphing. This setting allows the development of labs that can effectively foster a functional understanding of physics [6, 40, 44, 65-67].

The approach used in our development of labs using MBL-tools was inspired by, but not identical to, the pedagogical approaches applied in RealTime Physics and Tools for Scientific Thinking, and by research in Physics Education (see, for example, references [39, 40, 68]). In this paper I do not present a detailed analysis of the differences between our curricula and those mentioned above. Instead, I focus on an analysis of the tasks, as expressed in the lab-instructions, in terms of *discernment*, *simultaneity* and *variation*.

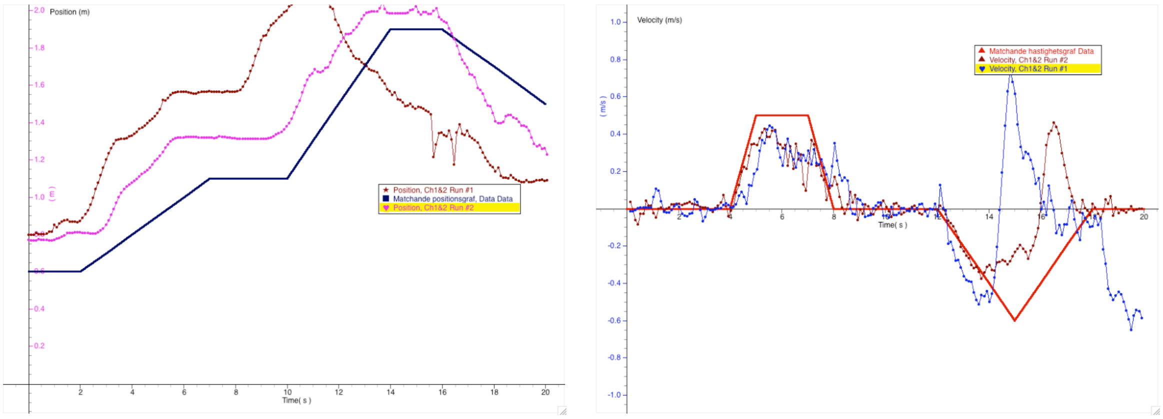

FIGURE 3. Example of a task that students attempt in a kinematics-lab. To the left is an s(t)- and to the right a v(t)-graph with curves that the students are asked to recreate, together with experimental graphs produced by students.

4.2 Examples of conceptual labs

Example 1. Here, I briefly discuss an example from one of the earlier tasks in a typical MBL-lab. In this task, students are asked to walk a trajectory that matches a given velocity–time graph. While moving, the participant and the other learners can see the experimental graph produced in *real-time* (see figures 3 and 4). Prior to this activity, students have solved tasks involving position–time graphs. Figure 4 shows an excerpt from the task presented in figure 3b.

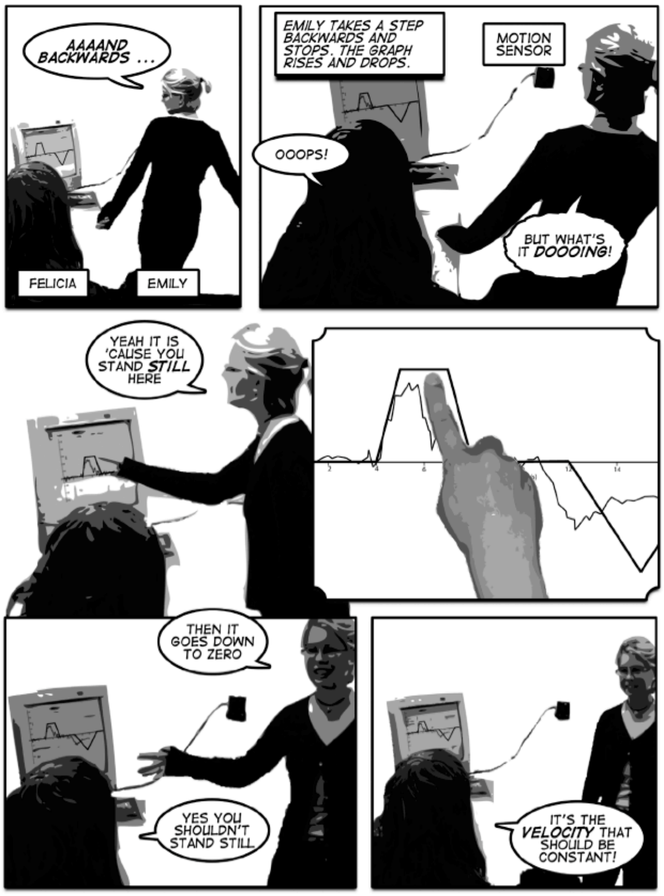

FIGURE 4. Drawings, based on video recordings, presented in the form of comic strips, to illustrate students' courses of action. This illustration is from a paper by Lindwall and Ivarsson [69] using our data.

What the technology does in this task is to bring velocity to the fore, i.e. it enters into the focal awareness of students. During the events represented in figure 4 Emily and Felicia realise the difference between position and velocity versus time graphs, i.e. they develop a more differentiated understanding of the physical concepts of motion. Other features of the situation, physical as well as non-physical, are not highlighted, i.e. some discernment has already occurred. It is also important that velocity is established as having a relationship with objects and events in the world. In order to complete the assignment, students have to understand this and they must also make important conceptual distinctions. Figure 3b shows data from students who struggle with the meaning of negative velocity and especially those for whom negative velocity with a decreasing magnitude was, incorrectly, translated into a change in their direction of motion.

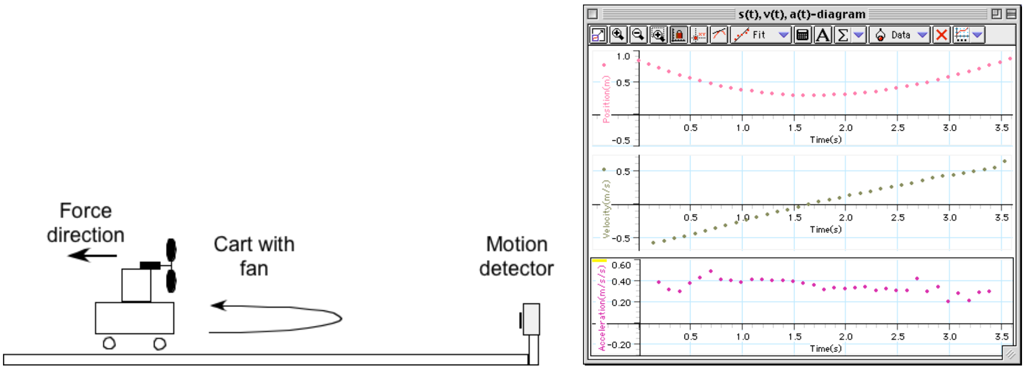

FIGURE 5. A typical setup in an MBL-experiment. A low-friction cart is pushed towards a motion sensor. A fan unit attached to the cart provides an approximately constant force in the opposite direction **to** the initial movement and, thus, the cart's direction of motion changes. The results are shown to the right. The results, for example, show that the acceleration is not zero at the turning point. Note that the fan unit provides a visible source of the force.

Example 2: *Acceleration with zero velocity*. In this activity students monitor the motion of a cart propelled by a fan (see figure 5a) that provides an almost constant "visible" force and, hence, almost constant acceleration. In this task the students should give the cart an initial push in the opposite direction to that of the force, so that the cart will slow down and reverse its direction of motion (they do this after studying the motion of the cart without reversing direction, but with acceleration in different directions). Students are first asked to observe the motion of the cart (without measuring it) and then to sketch their predictions of how the motion will be represented by position-time, velocity-time and acceleration-time graphs. After they have made their predictions the motion of the cart is once more observed and this time the MBL-equipment is used to measure the motion, and simultaneously display it as a graph (a typical graph is shown in figure 5b). To make accurate predictions, not only do the differences between position, velocity and acceleration have to be discerned, but also the relationships between these concepts. Velocity and position vary, but students have to recognise that the acceleration is constant and also that a zero velocity does not imply that the acceleration is zero. Asking the students to make predictions before the experiment is performed and comparing the outcome with their predictions facilitates comparisons between their thinking and reality. If there is any discrepancy we could regard this as a variation in the space of thinking models. Students thus have the opportunity to discriminate between different "models" and see which is the most powerful.

Example 3: *Motion with friction*. Traditionally in physics courses, friction is minimised in apparatus used to demonstrate the "validity" of the laws of motion (as exemplified by the invention of the air track as a teaching tool). However, in this experiment friction is deliberately introduced and varied using a special attachment to the cart, in order to introduce the frictionless "world" as a model and "limiting case". By varying the friction, students encounter both $v \propto F_{\text{external}}$ and $a \propto F_{\text{external}}$. Variation is, thus, introduced into different thought models illustrating how friction can be accounted for within a Newtonian framework.

4.3 History and results

A brief overview of the learning environments developed or studied in connection with this wider 'project' of developing conceptual labs is shown in figure 1. In this section I focus on results from teaching introductory mechanics. The learning environment developed for advanced mechanics has been described elsewhere [70, 71].

As mentioned above, this wider 'project' started in the 1994/95 academic year at Högskolan Dalarna (Dalarna University – a smaller Swedish University) with the development of the first labs using probeware and conceptual learning approaches. Some labs were developed for learning mechanics as well as for studies of electricity. A more fully-fledged application was available the following year, with a set of labs for a course in mechanics and heat and a course about electricity for trainee science teachers. However, at that time, no lab had been developed to deal with, for example, Newton's third law or the subject of rotary motion. Despite this, as shown in figure 6a, the students on this course achieved good results in all conceptual areas covered by the FMCE-test, except Newton's third law (which was not included in the lab-course). In subsequent years the conceptual labs were developed into a full lab-course and included courses in engineering mechanics. The results in figure 6a show that good conceptual learning was achieved and the data in table 1 show that the results were in line with some of the most well-known innovative curricula developed in the USA, such as Workshop Physics.

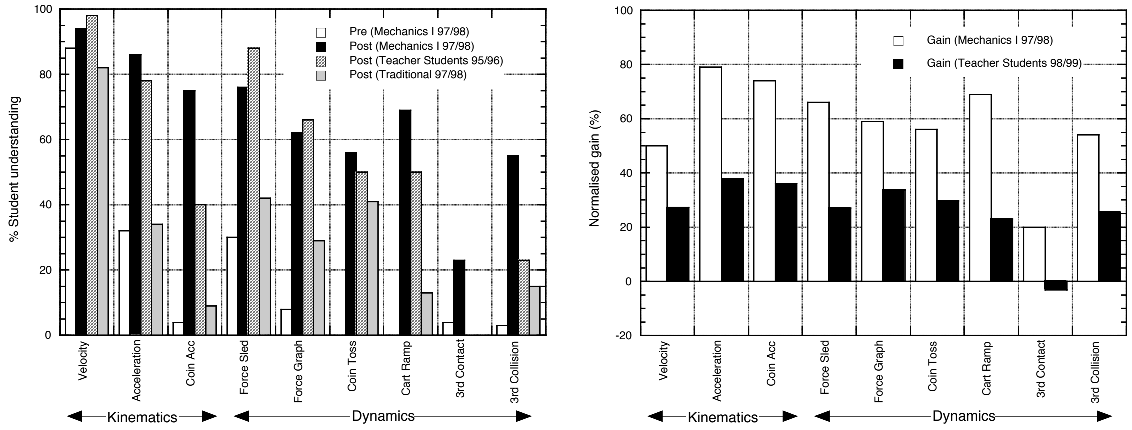

FIGURE 6. The results achieved, for different conceptual clusters, in the FMCE-test [42] as a result of different mechanics courses. In a) the data to the left are shown as 'absolute' values from pre- and post-testing. In b) the data to the right are shown as normalised gain (see above), comparing two courses that used the same probeware technology in labs, but different educational approaches.

In my absence during the spring of 1999 a lab-instructor rewrote the instructions using an approach that could be described as 'formula verification'. The instructor made a change that he believed was pedagogically good. Figure 6b compares the results of this changed curriculum with those for a course using the 'original' conceptual approach. The differences in achieved learning are quite striking. This example demonstrates that probeware and computers do not automatically produce good learning results, but that the educational design is crucial. In the following two years an experiment was carried out by another instructor. Some of the labs were returned to the original conceptual format, thus providing valuable data. For further details see references [6, 72].

I moved to Linköping University in the autumn of 1999. The experiences and pedagogical ideas from the courses described above were used to develop conceptual labs for an electric circuit theory course for electrical engineering students. The course included advanced topics, such as the application of transform-methods (phasor, Fourier and Laplace) and Fourier-series. After some years, the 'conceptual labs' were transformed into 'problem-solving labs' – the problem solving sessions and the original conceptual labs were merged into one type of session. Our analysis shows that this, together with the deliberate use of variation theory when designing tasks, has been especially successful in facilitating learning of complex concepts [33, 35, 73-75].

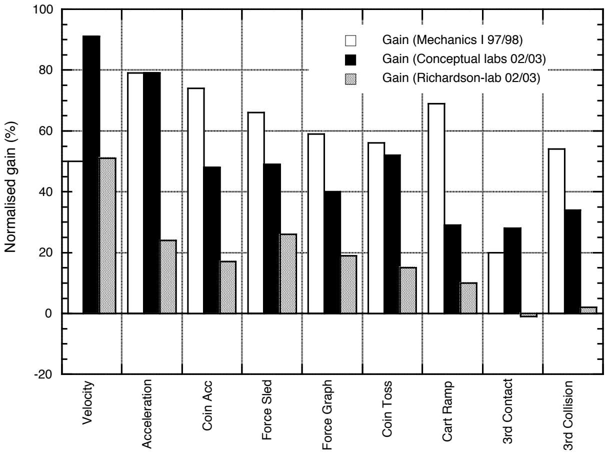

FIGURE 7. The results achieved, for different conceptual clusters, in the FMCE-test by students participating in the same physics course, but different lab-sections. As a comparison, Mechanics I from 1997/98 is included.

Some years later, in parallel with designing an experiment relating to learning electric circuit theory, original conceptual mechanics labs were further developed first in the context of a thematic education for future science teachers (academic year of 2001/02) and then, in the next year, by offering an alternative lab-course within a physics course for engineering students. In both cases a sub-set, consisting of four four-hour labs, was offered during which students' courses of action were recorded on video. In the case of the of the engineering students, all of them participated in the same lectures and problem solving sessions, so the only difference in teaching was the 16 h of labs. Figure 7 shows the differences in conceptual understanding, according to the FMCE-test. Although a full set of conceptual labs was not used, and the difference between groups was only whether they participated in 16 h of labs, the students who had attended the conceptual lab sessions clearly outperformed the other students on the test.

We are still in the process of analysing the video recordings from the labs. However, from our empirical data in the present state of analysis we see that students' courses of action are framed [76] by encounters with the instructions, the technology, the teacher and other students. When using the technology, students receive immediate feedback. In the process of constructing graphs they can see when they make mistakes. Students intertwine different interpretative resources as well as different experiential domains, such as graphical shapes, with narrative accounts of past actions. Learners must focus on the central aspect of the graph and, in order to complete the assignments, they have to make certain conceptual distinctions. The instructions for the task specify the process and the variance and invariance in the learning space. In order to solve the tasks successfully, the students have to deal with certain concepts in certain ways. Teachers not only design the learning environment, chose the technology and write the instructions, but also support students' activities in the lab, including encouraging students to shift their attention to central features of the graph while downplaying less important aspects. Students have a common perspective on the graph. Different interpretations of the graphical representation, experiment and subject-matter are negotiated by the students. Discussions are made an important component of the process of solving the task. It should be noted that the technology is present in all encounters.

Teaching Method/Course	Norm. Gain (FMCE)	Reference
Traditional (USA)	16%	Saul and Redish [77]
Traditional (Sweden)	18%	Bernhard [71]
Workshop physics (USA)	65%	Saul and Redish [77]
RealTime physics (secondary implementation, USA)	42%	Wittman [78]
ILD (example of secondary implementation, USA)	26%	Redish [79]
MBL 1997/98 (Sweden)	61%	Bernhard [71]
Physics 02/03 (Sweden) MBL-labs	48%	Bernhard [71]
ILD 05/06 (Sweden)	37%	Bernhard et al. [80]

TABLE 1. Learning gains for different courses [71, 77-80] as measured by the FMCE-test [42].

A variant of conceptual labs is the interactive lecture demonstration (ILD) [40, 80]. An ILD has some similar features to conceptual labs, including the use of probeware and specially designed tasks. However an ILD is performed in a lecture format in front of an audience. It differs from a common demonstration in its use of specially designed tasks and worksheets. The economic advantage of an ILD is that only one set of equipment is needed and the staffing cost is lower than for a traditional lab. However, learning gains, as measured by FMCE and shown in table 1, are not as high as for a well-implemented conceptual lab sequence. However, the gains are greater than for a traditionally delivered course and, therefore, ILDs are an interesting alternative.

5 CONCLUSION

The results from several different courses in physics and electrical engineering at two different Universities show that properly designed labs can provide a good environment for insightful learning. I conclude that the results from the projects described in this paper support variation theory. The results also point to the importance of conducting fine-grained empirical research and investigating the critical conditions for learning associated with each particular 'object of learning'. It is crucial in such investigations and when designing learning activities, that the researcher and the developer have deep and sound insights into the specific object of learning, i.e. the subject-matter studied, as well as theories of learning.

Acknowledgements
In conducting the projects described in this paper I have been supported by and have co-operated with many different colleagues. I'm especially grateful to Anna-Karin Carstensen and Oskar Lindwall. Thank You all!

This work has been supported by the Swedish National Agency for Higher Education, The Council for Renewal of Higher Education, through three different grants and by the Swedish Research Council.

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